Simulation study of a space based detector for UHECR observation

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The next generation of experiments devoted to the study of the cosmic rays spectrum above 10^{20} eV will be most likely done by means of space based detectors. In order to detect the fluorescence and Čerenkov signal generated by an EAS in atmosphere, severe requirements on the photon collection efficiency and on the triggering capability need to be met. In this paper we report about of preliminary studies of the triggering efficiency of a space based detector as a function of the main detector parameters. All results are obtained by means of a detailed simulation of the shower development, atmospheric response, detector geometry and electronics and trigger behavior in realistic conditions based on the ESAF package, the EUSO Simulation and Analysis Framework[4].

Introduction

In the last decades few tens of Extensive Air Showers induced by the interaction of a primary UHECR of energy $\gtrsim 10^{20}$ eV in the atmosphere have been detected by ground based experiments. Their origin and the presence of the Greisen-Zatsepin-Kuzmin (GZK) feature at the higher energies nowadays are still under debate mainly due to the small number of detected events. UHECR reach the Earth with a very low flux ($\mathcal{F} \approx 0.01 \frac{\mathrm{events}}{\mathrm{year\ km^2\ sr}}$ for energies $\gtrsim 10^{20}$ eV) and therefore a huge target as well as a complex and sophisticated experimental apparatus is required to observe them.

A new and very promising approach was proposed the for first time in 1979 by John Linsley. The scintillation light of the atmospheric nitrogen, excited by the charged particles of the showers can be observed by a space-borne detector watching the atmosphere from space during night-time. A telescope orbiting at several hundred kilometers altitude with a large field of view optics can achieve an enormous instantaneous geometrical aperture, grant the full-sky coverage and possibly identified the EAS induced by weakly interacting primary particles starting deeply in the atmosphere.

Due to large observational distance only a tiny fraction of the fluorescence photon reach the detector. Therefore, the instrument must be designed as a large aperture, UV sensitive, ultra-fast and low noise digital camera. Moreover as a space device, it must satisfy strict constrains on mass, power consumption along with high reliability and long-term stability in the space environment.

The requirements on each parameter are bounded to the mission's physics objectives. The final aim of of this preliminary study is to settle a set of requirements for space based UHECR experiments. Due to the challenging constraints of this observational approach,a full monte carlo simulation in realistic conditions is the essential tool to establish a solid ensemble of requirements taking in account all the critical aspects. For that we have used the ESAF package, developed for the EUSO experiment[1][2] and is described elsewhere [4]. EUSO,

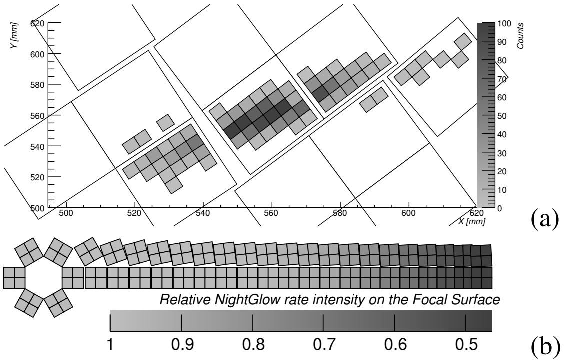


Figure 1. (a) $2 \cdot 10^{20}$ eV, 60^o zenith angle shower image on the focal plane (Config B). (b) Relative nightglow rate distribution on a slice of the focal surface.

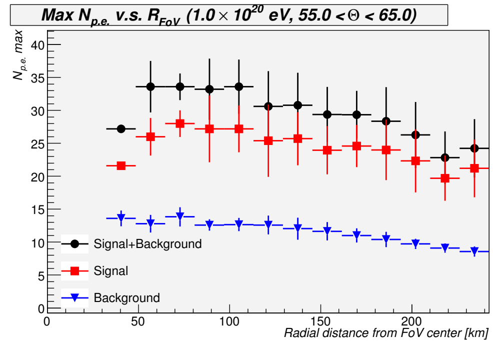


Figure 2. The shower maximum signal is compared with the background as a function of the distance from the center of the FoV.

the first ESA space mission for the measurement of the UHECR, is based on up-to-date technology and has successfully completed the Phase A. ESAF is able to simulated EUSO in great detail as according to the design described in the Phase A study final report[3]. The main EUSO parameters are summarized in table 1. The ESAF high degree of flexibility grants the possibility to run and compare different configurations on the same ground.

Among the others, a special role is played by the instrument's photon collection efficiency is directly connected to the energy threshold. To probe the effect of an enhanced optics aperture on the energy threshold, we have simulated 4 different detector, identical in the design, but differing in size.

Parameter	Value	Parameter	Value
Detector's Altitude	$H_{det} = 420$ km	Gate Time Unit	$GTU = 2.5\ \mu s$
Field of View (half)	$FoV = 30^o$	Pixel size	on ground (nadir): 0.8×0.8 km^2
Photo Detection Efficiency	$PDE = 0.14$		on the FS: 4.3×4.3 mm^2
Optic's PSF	Gaussian, $\sigma = 2.5$ mm	Background noise radiance	$R \approx 500 \div 1000 \frac{\mathrm{photons}}{\mathrm{m^2\ ns\ sr}}$
Optic's throughput:	$t = a - b \cdot \theta^2 - c \cdot \theta^4$	($300 \div 400$ nm)	
	$a = 0.44, b = 0.071, c = 0.59$		

Table 1. EUSO RedBook detector's parameters

The base configuration (A) is a 2.5 m diameter telescope, (B), (C) and (D) are 4 m, 8 m, and 12 mt diameter telescope respectively. These detectors have been tested using a sample of 30000 proton showers with energy between 10^{19} eV and 5×10^{20} eV, energy spectrum $\frac{dN}{dE} = e^{-E}$ (10^{19} eV $\leq E \leq 5 \cdot 10^{20}$ eV) and uniformly distributed in zenith angle. US-Standard clear sky atmosphere has been assumed.

The background

The night Airglow (nightglow) is possibly the most important source of background which a space borne telescope will be sensitive to, for moonless and clear sky with no pollution light. The expected value is reported in table 1. Heuristically, the background rate is maximum in the center of the focal surface and lower at the edges, decreasing with the throughput of the optics. However, the exact distribution of nightglow photons on the focal surface is difficult to calculate analytically. As a matter of fact, the background is the sum of both the photons focused by the optics, and the scattered ones. To avoid this problem, for each optical system implemented in ESAF and for the configuration (A), we traced several million of photons distributed in incidence angle according to the expected nightglow. We have then computed the the nightglow rate per pixel according to the resulting photon's distribution on the focal surface, the pixel size and the photomultiplier's quantum efficiency.

The signal

The air fluorescence induced from an UHECR induced EAS appear as a thin luminous disk, whose intensity is proportional to the number of charged particles. The EAS develops in the atmosphere approximately at the speed of light. The fluorescence light at the maximum and the total integrated fluorescence are proportional to the primary energy.

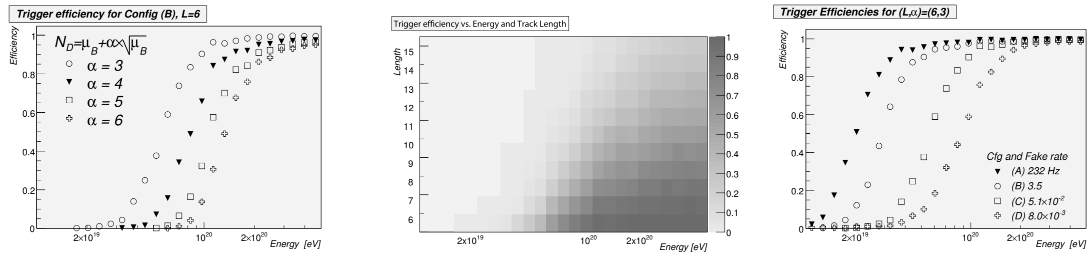
On the focal surface the EAS appears as a faint spot, mostly included in one pixel, increasing in intensity up to its maximum and gradually fading away. The full development of the shower draws a track in space and time whose length and intensity depend mainly on the primary energy and incident angle and secondly, on the position in the field of view (fig. 2). Only the EAS whose signal is intense and long enough to stand over the background can provide useful information on the primary. This means that even if the maximum of the less energetic EAS is strong enough to overtake the background, the track structure might be lost among the fluctuations of the background. The last sentence can be translated into two requirement on the signal. First, at pixel level, a background dependent threshold can be established: $N_D = \mu_B + \alpha\sqrt{\mu_B}$, where μ_B is the mean number of background counts per pixel per GTU, and α a coefficient depending on the requested background rejection efficiency. Secondly, it must form a track. Starting from the first active pixel, the next active one in the next GTU must be the same pixel or one of the neighboring. The minimum number of consecutive active pixels, the track length L, can be assumed as the second requirement a signal must satisfy to be recognized as a possible EAS candidate.

The contiguity tracking trigger algorithm

We have studied the trigger efficiency using the contiguity tracking trigger (CTT) developed during the EUSO Phase A. It works at the Elementary cell front-end level, that is an ensemble of 2x2 closely packed multianode photomultipliers. Actually, in this context every elementary cell is an independent unit of 144 pixels (fig. 1a,b). The CTT is a simple algorithm that checks the signal contiguity in space and time, as explained in the previous section. Thought to be integrated in the front-end chip as first level trigger, it can be implemented using purely combinatory circuits with low cost in term of power and mass budget. N_D and L become the intensity and the minimum length thresholds. Due to the background non uniformity on the focal surface, is more convenient to write N_D as a function of the parameter α. Fixing α is equivalent to require an adaptive threshold, that depends on the local background rate.

Then the fake trigger rate for uniform poissonian background is then easy to compute . The mean number of active pixels in one GTU is $M_1 = 144 * p(\mu; N_D)$, where $p(\mu; N_D)$ is the probability for a pixel to count at least N_D photoelectrons in one GTU. In all GTU after the first one, the probability that the random nightglow can activate a pixel neighbor to one activated in the previous GTU is $\approx 9p(\mu; N_D)$. Therefore the probability to have a track of length L is $P_L \approx 9^{L-1}[P(\mu; N_D)]^L$.

The maximum acceptable overall fake trigger rate is constrained mainly by the available telemetry resources. Thus, the maximum fake CTT rate is then limited by the time the 2^{nd} level trigger to further process the data. The final number depend of course on the details on the 2^{nd} level trigger, but realistic estimation based on the current technology sets this limit to ≈ 100 Hz.



(a) (b) (c)

Figure 3. (a) Trigger efficiencies for the (B) configuration, for different values of alpha. (b) The (B) configuration trigger efficiency vs. EAS energy a function of L for $6 \leq L \leq 16$. $\alpha = 3$. The fake trigger rate is calculated for $R = 500 \frac{\text{photons}}{\text{m}^2 \text{ ns sr}}$. (c) Trigger threshold for the (A), (B), (C), and (D) configurations using the trigger pattern $(6, 3)$

Due to the large background disuniformities, N_D cannot have the same value for every channel on the focal surface. Instead, we used α as one of the variables of the trigger, automatically taking the disuniformities into account. In figure 3a the behavior of the trigger efficiency as a function of α is shown.

We have scanned the region of the (L, α) parameter space with $6 \leq L \leq 16$ and $\alpha = 3,\ 4,\ 5,\ 6$.

In fig. 3c is shown a comparison of the efficiency curves obtained with the trigger pattern $(6, 3)$ for the different configurations. The fake trigger rate for is reported there as well. $L = 6$ is the shortest length we have simulated so far. The threshold shifts as expected toward lower energies as the square root of the scale factor. The main difference between the curves is the fake trigger, that is higher than 100 Hz and decreases very rapidly with the increase of the photon's statistics, that is the aperture of the optics. The efficiencies can be possibly increased at lower energies decreasing L to $L = 4, 5$ and $\alpha > 3$, taking in account the EAS track length is indeed shorter. In that case and for the configuration (A), the fake trigger rate is expected not to be larger than 40 Hz.

Conclusions

The study on the performances of UHECR space detectors has just begun. We have shown the preliminary tests on the behavior of the trigger threshold as function of the optics aperture. Still, more improvements are expected from the further optimization of the thresholds. The final study will discuss optimization all the relevant parameters for an UHECR space detector, including not only the simulation, but also the reconstruction efficiency.

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